An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques

Christopher K. R. T. Jones
Department of Mathematics
University of North Carolina
Chapel Hill, NC 27599-3250
phone: (919) 962-9607 fax: (919) 843-0428 email: ckrtj@email.unc.edu

Award Number: N00014-04-1-0215
http://www.math.unc.edu/people_christopherjones.html

LONG-TERM GOAL

The full use of Lagrangian observations in ocean prediction could significantly advance the Navy's ability to predict ocean conditions. The primary goal is the development of a fully operational, integrated data assimilation scheme will afford a full naval predictive capacity in fixed ocean regions which can be comprehensively surveyed by Lagrangian measuring devices. A key part of this aim will be to develop the ability to assess efficient Lagrangian deployment systems. This will be based on the use of dynamical systems ideas that can generate optimal strategies for deploying Lagrangian observational devices and their associated sensors. The optimal deployment coupled with an effective Lagrangian data assimilation strategy will form the basis of an integrated prediction scheme for the ocean that can feed on both purely Lagrangian and mixed source data.

OBJECTIVES

This project aims to develop an operational technology for assimilating Lagrangian data. This new Lagrangian data assimilation platform is expected to be particularly effective in ocean regions where coherent structures such as ocean eddies dominate the circulation. The focus is on: 1) The extension of our Lagrangian data assimilation (LaDA) approach into a flexible platform, through which a variety of moving instrument measurements, which may not be viewed as purely Lagrangian in a conventional sense, can be integrated; 2) The design of observing systems that take full advantage of all moving instruments; 3) The formulation of automated algorithms for optimal deployment strategies of the moving instruments so as to maximize the information content of the observations; and 4) The incorporation of dynamical systems theory to enhance our predictive skill, in particular trough deciphering coherent structures and tracer fields associated with them.

We use the term “Lagrangian data” in the broadest sense, including the positions of various moving instruments along the trajectories as well as time sequence of the tracer fields. Autonomous underwater vehicles (AUVs) that glide or maneuver in the ocean are new types of moving instruments that will be incorporated into our extended LaDA platform as a part of the control variables. AVs have come to be a stable and reliable means to measure water properties. The platform will be ideal for designing an autonomous ocean sampling network, adaptive observations, and optimal deployment plans of such moving instruments. The extension will also have the capability to handle high-dimensionality and nonlinearity of the operational ocean models. An example of the structure of the tracer fields is an ocean color obtained by satellite.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of North Carolina,Department of Mathematics,Chapel Hill,NC,27599-3250**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

A comprehensive LaDA platform will be built upon balanced integration of data assimilation techniques and dynamical systems concepts. Recent developments in the theory and use of dynamical systems concepts for Lagrangian analysis will add a new dimension to the LaDA platform. Incorporating the geometrical approach will offer a much needed template for the observing system design of the LaDA platform. In return, accurate estimation and forecast of the Eulerian flow field by assimilating such data will further strengthen the reliability of the observing system with moving instruments.

APPROACH

Our approach is to use LaDA as a basis for the development of an operational technology that accommodates the assimilation of data from a variety of measurements by any type of moving instruments including drifters, floats, and AUVs. Such a platform is being developed through a hierarchy of models. Fundamental issues are addressed using idealized model flows. Basic tests are being performed on intermediate model flows, the double-gyre, shallow-water model with various wind forcings, and progressing to the realistic general circulation model for operational application in the Gulf of Mexico. We will investigate to what extent Lagrangian data can be used to aid in the estimation of the three-dimensional flow evolution. We will improve the LaDA method to better deal with the chaotic nature of the Lagrangian dynamics. We address the localization and inflation issues that will help simplify estimates of error covariance and develop a Lagrangian Ensemble Kalman Filter (EnKF).

Ideas from dynamical systems theory will be employed at every stage to provide a solid, mathematical foundation while casting conceptual simplicity on the complex platform. This project is a joint project by the two co-PIs, K. Ide (UCLA) and C.K.R.T. Jones (UNC-CH). G. Vernières is a postdoctoral fellow who works on the LaDA platform for the Gulf of Mexico. H. Salman is a postdoctoral fellow who works on the applications of the dynamical systems theory to LaDA. Liyan Liu is a graduate student who researches the vertical propagation of the information by the LaDA. Amit Apte is a postdoctoral fellow working jointly with Andrew Stuart (University of Warwick, UK) on applying Langevin sampling techniques to Lagrangian data assimilation.

WORK COMPLETED

Progress is being made in advancing Lagrangian data assimilation towards operational use. This is being achieved through a coordinated effort to test and adjust the LaDA scheme together with designs and tests of optimal deployment strategies.

Issues essential to the smooth functioning of LaDA have been investigated during the past year. Due to the very nature of Lagrangian motion, the dynamics is usually chaotic at least in many sub-regions, filter divergence can ensue in a manner that is a challenge to anticipate. The underlying cause is related to the distinguished hyperbolic trajectories that govern the flow template and make the local tracers separate at an exponential rate. A sophisticated quality-control method is being developed by combining the concepts of the dynamical systems theory with an expectation-maximization (EM) algorithm.

Much Lagrangian data is collected with surface drifters. A natural question arises as to how effectively this data can be used in estimating the full three-dimensional ocean flow. We have implemented LaDA

in a two-layer point vortex model. The potential for the vertical propagation of the observed information is examined through testing its efficacy in parameter estimation.

Towards the development of an operational strategy for assimilating Lagrangian data, the strategy for optimal drifter deployment is investigated further based on the flow template regulated by the invariant manifolds using the EnKF-based LaDA. Currently the scheme is applied to a single-layer shallow-water ocean model. We have discovered that a mixed strategy of placement, near hyperbolic and elliptic points in the flow, is the most effective when the observational data is assimilated through LaDA.

We have implemented a multi-layer reduced gravity model of the Gulf of Mexico (GOM.) This modeling setup has been shown to be the simplest representation of the GOM that simulates the shedding of eddies, known as the key dynamic effect in the GOM. It is a first step toward a detailed representation of the physics of the GOM. The horizontal discretization uses a curvilinear grid. It has a horizontal resolution of about 5 km in the region of the loop current. We impose a sinusoidal shaped current at the Yucatan channel and the strait of Florida with respective widths of 160 km and 150 km. In order to conserve the total mass in the Gulf, the inflow transport matches the outflow transport. This configuration allows us to reduce the number of degrees of freedom to a minimum without sacrificing the resolution near the region of interest. The structured curvilinear grid of the horizontal discrete domain was created using elliptic grid generation techniques. The boundary of the grid, illustrated in Figure 1, follows the coastline.

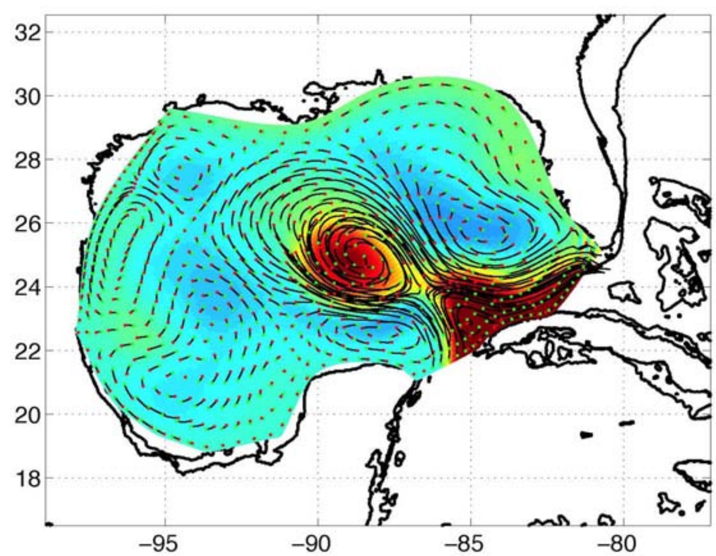

Figure 1. Surface Lagrangian and Eulerian fields of the Gulf of Mexico by the multi-layer reduced gravity model [Colors represent the sea surface height (Eulerian field). The black lines are 625 drifter trajectories over eight days (Lagrangian field). The green and red dots represent the departure and arrival points, respectively.]

For the assimilation of the tracer field, we have added a functionality to compute the passive tracer field as represented in Figure 2.

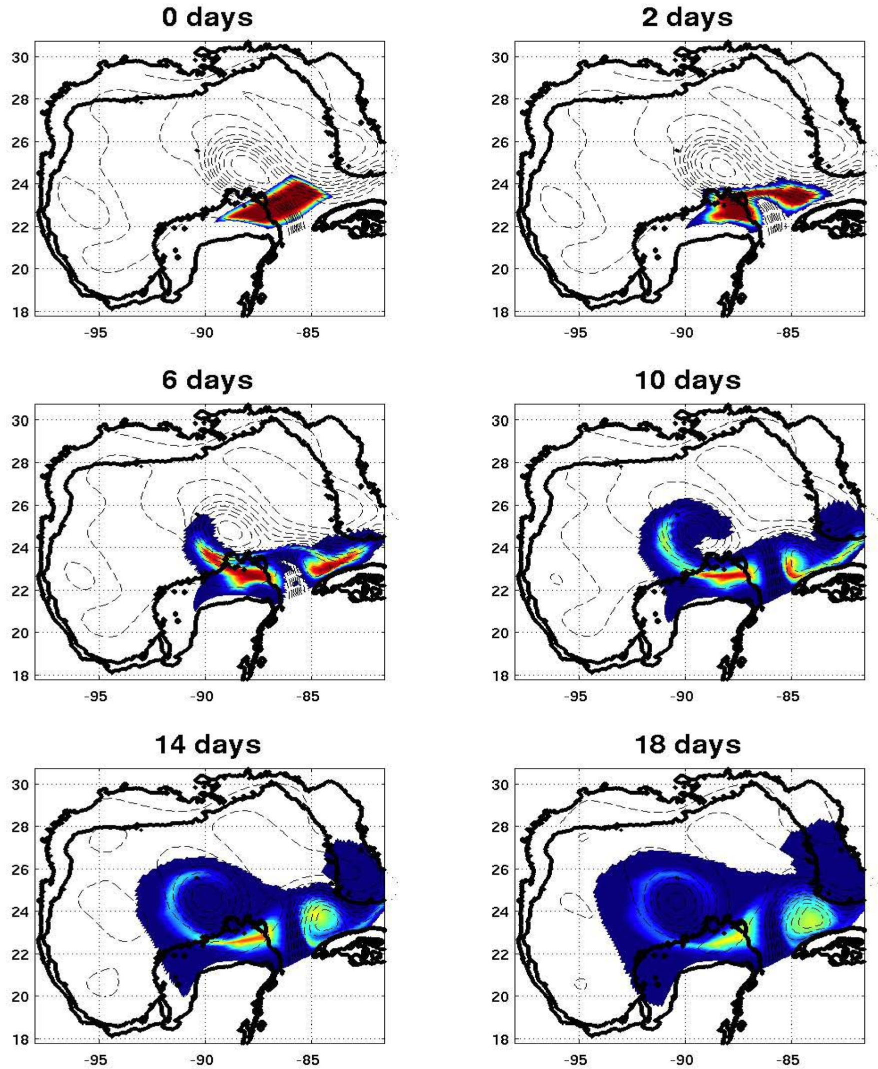

Figure 2. Lagrangian tracer fields of the Gulf of Mexico by the multi-layer reduced gravity model [Colors represent the normalized concentration of the tracer. The dashed black lines represent the sea surface height.]

RESULTS

By combining the EM-algorithm, the tracer control scheme can detect the hyperbolic effect more reliably and promises to lead to a robust LaDA method.

The LaDA method has been shown to afford a successful estimation of the highly-idealized multi-layer point vortex model within the Rossby radius of deformation. The barotropic mode plays a key role as expected. Testing on a two-layer model is natural as for the multi-layer model configuration of Gulf of Mexico, the current is confined to the two upper most layers with the ratio of transports between the two upper layers being kept constant. The upper most layer carries 80% of the total volume transport.

For the development of theoretical deployment strategies, the problem is made complicated by the fact that the positions of Lagrangian data are continuously changing with time by the underlying flow field.

In order to tackle this problem, an understanding of how the underlying flow field governs the motion of Lagrangian data is required. This problem is most naturally addressed using recent ideas borrowed from dynamical systems theory to extract Lagrangian coherent structures. These structures have been studied extensively for geophysical flows in recent years and are understood to orchestrate the evolution and notion of material particles.

Figure 3 (left) illustrates the locations of several key structures that were identified for our double gyre flow experiments. Also shown are the deployment sites of sets of drifters in relation to these various structures. Figure 3 (right) illustrates the convergence of the data assimilation method for several different sites. For reference purposes, a case with no data assimilation is included. The figure compares four different cases; uniformly released drifters, drifters released at saddle trajectories, drifters released within coherent vortices, and finally a combination of saddles and centers. In all the cases considered, nine drifters were used for the data assimilation. The results clearly show that the uniform launch produces the optimum convergence although at the expense of having to release the drifters in regions remote from one another. In stark contrast, targeting Lagrangian saddle points appears to produce equally accurate results at long times but with only three different release sites for the nine drifters. This occurs because Lagrangian saddle points can disperse drifters over a wide region providing effective sampling of the entire flow field. Therefore, by exploiting the internal dynamics of the governing flow field through the targeting of Lagrangian coherent structures, we are able to optimize the performance of our method through the optimal deployment of drifters.

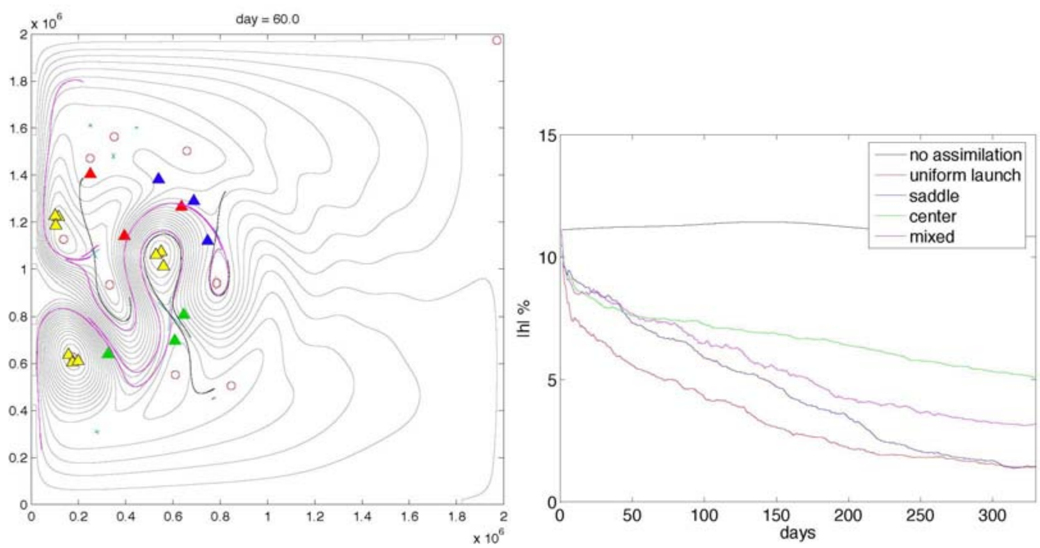

Figure 3. Results for directed drifter deployment strategy. Left pane: Lagrangian coherent structures superimposed on the height field at day 60. Right pane: Error in the height field.]

The LaDA-EnKF works effectively for ocean data assimilation using a shallow-water model (Figure 2) by applying the localization radius. An advantage of this method over other existing methods is that the assimilation time interval can be as long as the Lagrangian correlation time scale.

Judicious computation of the error correlation and innovative construction method for error correlation are crucial in the coastal data assimilation system using the variational approach.

IMPACT/APPLICATION

Much data for the ocean is Lagrangian in nature and our techniques promise its effective use in predictive models. We are developing a refined scheme to incorporate this data into models of specific ocean regions. The approach is adaptable to the incorporation of all data comng from moving instruments, including floats, AUVs etc.

As the scheme is developed to the point of efficacy in real time, its use in naval operations will have signficant application. Its impact will be further enhanced by the optimal dployment strategies being uncovered through the application of dynamical systems ideas.
The development of LaDA in a realistic ocean model of GOM is being carried out on a model that is designed to offer a smooth transfer to operational naval models.

RELATED PROJECTS

1. NSF CMG Heavy Tailed Distributions in Geophysical flow: Physical Mechanisms and Data Assimilation, in collaboration with Richard McLaughlin, Roberto Camassa and Christopher K.R.T. Jones (UNC-CH) and Didier Sornette (UCLA).

2. Uncovering the Geometry of Ocean Flows: Implications for Predictability and Experimental Design ONR Grant number: N000014-03-1-0174

3. SAMSI program on "Data Assimilation in Geophysical Systems" see: http://www.samsi.info/programs/2004geophysprogram.shtml

PUBLICATIONS

Chin, T.M., K. Ide, C.K.R.T. Jones, L. Kuznetsov and A.J. Mariano, 2006:
Mapping, Assimilation, and Optimization Schemes, in Dynamic Consistency and Lagrangian Data in Oceanography: Analysis and Prediction of Coastal and Ocean Dynamics, Cambridge University Press, Accepted

Ide K. and C.K.R.T. Jones, 2006: Controlling the filter divergence in a Lagrangian data assimilation, to be submitted

Liu, L., K. Ide and C.K.R.T. Jones, 2006: Demonstration of vertical propagation of information from the assimilating of Lagrangian data, to be submitted

Salman, H., L. Kuznetsov, C.K.R.T. Jones and K. Ide, 2006: A method for assimilating Lagrangian data into a shallow-water equation ocean model, Mon. Wea. Rev., 134, 1081-1011.

Salman, H., K. Ide, and C.K.R.T. Jones, 2006: Targeted observation for optimal deployment in a Lagrangian data assimilation system, to be submitted.

HONORS/AWARDS/PRIZES

Visiting Fellow University of Sydney, June 2006

Awarded Simons Professorship at Mathematical Sciences Research Institute, to be held Spring 2007.